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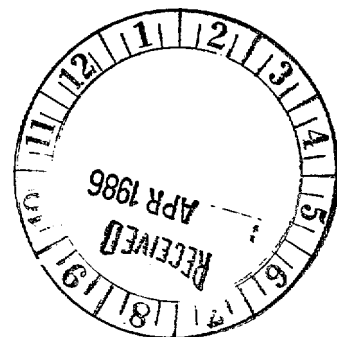
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APPENDIX VIII

ICE MOVEMENT IN THE EASTERN BEAUFORT SEA
RELATED TO WIDENING OF THE CAPE BATHURST POLYNYA

by

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Ice Movement in the Eastern Beaufort Sea Related to Widening of the Cape Bathurst Polynya

INTRODUCTION

It has long been recognized that pack ice along the Beaufort coast of Alaska undergoes a net westward movement during winter months. In recent years radio position buoys have been used to monitor this movement (Colony, RU 98). On the other hand, satellite imagery is available continuously from 1972 through the present. This report describes an attempt to use satellite imagery to monitor this movement and related phenomena.

The problem is somewhat more difficult than it would appear at first, because although specific ice features can be tracked even several weeks at a time, long periods of cloudiness occur after which many or all former ice features are obliterated. There is, however, one very prominent ice feature in the Beaufort Sea which serves very well as a record of westward (and some eastward) ice movements. This is the large north-south oriented recurring lead on the eastern side of Mackenzie Bay. Here we have called this the Cape Bathurst Polynya (see Figure 1).

During the winter this polynya is nearly always open and is subject to periodic widening as the pack ice in the Beaufort Sea moves westward. Thus, the widening events of this polynya serve as a measure of the westward transport of ice in the Beaufort Sea. Furthermore, except under the most extreme circumstances, even though the ice edge is subject to freeze-back, it is usually possible to locate the former ice edge after

a period of cloudiness. Thus the Cape Bathurst Polynya serves as a measure of cumulative ice displacement over a period of time.

As the pack ice moves westward, opening the polynya at the eastern side of the Beaufort basin, left-lateral motion takes place between the Beaufort pack and the fast ice along the Beaufort coast. If there is an offshore component to this motion then a lead appears along this line. If there is an onshore forcing, shear ridging results.

This work describes a survey undertaken to investigate the typical range of ice movement incited by the Cape Bathurst Polynya from approximately mid-February through mid-June, to highlight extreme events for more careful examination, and to attempt to correlate ice movement with events such as ridge building.

Two sites were selected for measurement of ice motion:

Position A off the Kongakut River delta was chosen to describe roughly north-south or offshore movement. Position B in the MacKenzie Delta was chosen to describe roughly east-west movement; these measurements document movement associated with opening or closing at the southern end of the Cape Bathurst Polynya. The location of Positions A and B are shown in Figure 1.

NOAA images in the visible range (0.5 to 1.2 μm) were examined for the presence of openings and closings of the polynya. Measurements were taken daily starting from mid-February when cloud cover and ice conditions allowed, and ending in June when the ice retreat was so rapid that it was impossible to differentiate between ice movement and ice melting. Measurements were not taken for the years 1979 and 1980 because too few images were sufficiently cloud free to give a realistic measurement of total ice movement.

Landsat images in the near infrared range were examined to study the unusual events revealed by NOAA imagery in more detail.

RESULTS

Figures 2 and 3 and Tables 1 and 2 summarize cumulative ice displacement. Off the MacKenzie Delta, the Cape Bathurst Polynya opened to the greatest extent in 1975 and 1978; a moderate amount in 1976, 1977, 1981, 1982, and 1983; and very little in 1974. Large gaps in the plots indicated periods for which cloud cover and ice conditions made it impossible to detect movement. After each gap, the cumulative total was resumed by adding the best conservative estimate of the widening which had occurred during the period of cloudiness. This may have been fairly accurate in the case of a clearly observable former ice edge later visible as a boundary between two ice thicknesses, or merely a minimum separation represented by a very newly opened lead. Thus, the cumulative totals for all years are probably underestimates. For the eight years studied, the average westward opening of the Cape Bathurst Polynya was 134 km, with a standard deviation of 55 km.

Off the Kongakut River on the east-west left-lateral lead, the ice moved the greatest amount in 1975, 1976, 1981, and 1982, and the least amount in 1974, 1977, 1978, and 1983. These measurements are less meaningful than the MacKenzie Delta set because cloud cover is more frequent in this area, and the leads which do form are smaller and harder to measure. The average opening of this lead was 44 km with a standard deviation of 36 km.

Referring to Figure 2, one can discern the following general pattern for ice displacement:

Rapid ice displacement almost always occurs in June. This is obviously **part** of the mechanism of **spring** break-up. At this time of the year it is difficult **to** differentiate between displacement due to **actual** movement of the pack ice and displacement due to melting of the pack ice.

Rapid ice displacement can also **occur** in March. This apparently happened in three of eight years studied, so it is a relatively common phenomenon. **All** ice displacements measured at this time would be due to actual movement **of** the ice. However, as ice **may be** forming over the open water in the leads as the leads open, it is possible that the actual movement of the pack ice is underestimated.

The years 1974 and 1975 represent the extremes for the years examined (Tables 1 and 2). The years 1974 and 1976 **have** periods of no observations of particularly long duration. In April of 1974 the visibility appeared to be sufficiently good to detect ice features, but no significant **leads** appeared. The year 1974 apparently was a year of extreme stability.

The year 1975 was one of extreme activity. Much of this extreme activity occurred in the second half of March **and** the resultant displacement boosted the total yearly westward ice displacement sufficiently to remove any similarity 1975 might have had with 1981, another **active**, ice displacement year, for the rest of the spring.

Figures 4, 5, and 6-from NOAA imagery for **March 15, 26, and 28, 1975** and **Figure 7** from Landsat imagery for **April 5, 1975** document the sequence of events for this extremely active **period**, as **well** as illustrate some of the more common place events associated with ice movement.

Figure 5 shows-the Cape Bathurst Polynya which has.' been descri bed in detail by Smith and Rigby (1981). These authors state that a recurrent crack and lead system develops between the landfast ice and arctic pack ice along the coast west from Cape Bathurst to beyond Pt. Barrow. This feature changes little in position from year to year and is thought to mark the boundary of the seaward fast ice. No mention is made of the prominent lead visible in Figure 5 north of this recurrent lead which connects Pt. Barrow to the Cape Bathurst Polynya at a point off Cape Kellett on Banks Island.

Figures 5 and 6 show the typical banded appearance a lead assumes as it simultaneously opens and freezes. This phenomenon often accompanies the widening of the Cape Bathurst Polynya which forms offshore of Banks Island and the Bathurst Peninsula.

Figure 4 shows the westward drift of a floe which broke off the fast ice on March 14; Figure 6 shows two much larger floes in the process of breaking free of the fast ice; and Figure 7 shows the aftermath of two of these floes colliding with the pack ice between Herschel Island and Barter Island.

The widening of the Cape Bathurst Polynya during the period March 25 to March 30, 1975 was measured more carefully than for the survey as a whole; the results appear in Table 3. These measurements reveal the following; not only is the ice displacement extremely variable from day to day, but on the same day it is extremely variable from place to place. Moreover, it is important to measure not only the open water, but also the frozen portion from the pack ice, as there is evidence that newly formed open water may slowly freeze in the course of the day.

DISCUSSION

Landsat imagery was examined to discover a relationship between events such as **ridge** building and extreme events off the Mackenzie **Delta**.

It is **useful to** consider the relative precision of measurements made on NOAA imagery with measurements made on Landsat imagery. These results are summarized in Table 4. The conversion factor between Landsat and NOAA imagery is 9 to 1 mm for the years 1974 to 1979, and 7 to 1 mm for the years 1980 to 1983; the features were measured to the nearest 0.1 mm. The conversion factor for Landsat imagery is 1 mm = 1 km, and the features were measured to the nearest 0.1 cm. Thus, theoretically, both NOAA and **Landsat** imagery were measured to ± 1 km. However, the NOAA measurements were inherently less accurate than the Landsat measurements for three reasons:

It is much more difficult on NOAA images to guarantee that one is measuring at the same location for measurements on successive days, and it is much harder to make judgments of the location of the ice edge because the appearance of the **ice changes** so much with the condition of the ice. When the ice changes character sometime in mid-May, these difficulties are even more pronounced. Moreover, NOAA imagery displays distortion due to the curvature of the earth. This latter error was never more than 1 km foreshortening in 10 km. It is concluded that one is doing very well to measure displacements from NOAA images to ± 2 km.

No Landsat images were available for March 25 thru 30, the dates spanning the event displayed in Figure 6. However, five were available for March 15 thru 19 (Figure 8) and two were available for April 4 and 5, 1975 (Figure 7). Table 5 shows ice displacement measured within the

Cape Bathurst Polynya off the MacKenzie Delta on NOAA imagery and

movement of four ice features off Herschel Island which are measured from Landsat imagery taken March 15-19. These ice features are: (1) a floe breaking away from the moving ice pack; (2) an unattached floe; and (3) the edge of the pack ice; and (4) a small floe in a lead in the pack ice.

Figure 8 locates these ice features in relation to ice conditions on April 5 and 6. These results show that the motions are coherent but not strongly related. Thus, an opening of the Cape Bathurst Polynya by 10 km does not imply that all ice in the Beaufort Sea moved 10 km westward. It would seem reasonable that in general, compaction (including ridge formation) would decrease the net displacement as one moves further west.

Examination of Landsat imagery (Image 1986-20354 76/10; Figure 7) from April 5 reveals that no recognizable features from the period March 15 thru 19 are present. However, a new ridge system of perhaps 100 km in length is in place 100 km offshore from the Kongakut River. Other features which appear to be a family of smaller ridges are located approximately 100 km north of Barter Island. There also appears to be fragmented ice. One explanation for the above observed features is that the phenomenon that was responsible for the extreme ice displacement off the MacKenzie Delta on March 20 thru 25 was also responsible for breaking up the ice features observed near Herschel Island from March 15 thru 19 and creating the fragmented ice and ridges observed on April 5. "

On March 14, a floe broke free of the fast ice off the MacKenzie Delta at 70° N, 135°30' W. The path and rate of movement of this floe was followed on NOAA imagery. This movement is described in Table 6. The area of this floe was roughly 200 square kilometers on the 15th. On

March 28, two **larger** floes broke free of the fast ice. One broke off north of the **Kongakut** River delta at **70°N, 142°W** and was **1000** square kilometers in area. The other broke off Herschel Island at **69°45' N, 138°30'W** and was 650 square kilometers in area. Apparently around March 30, these two **large** floes and the **smaller** March 14th floe collided with pack ice north of Barter Island and produced the features seen on **Landsat** images 1985-20303, 1986-20361 and 1986-20354 for April 4 and 5: the ridges described above and two **small** remnants of the floes first observed on **NOAA** imagery. The **larger** remnants measure 600 square kilometers and 350 square kilometers. The dimensions of the feature hypothesized to be the March 14 floe are 18 X 6 kilometers.

The largest floe described above appears to have removed enough ice from the fast ice edge as it broke free between Herschel and Barter Island to have created a new **ice** edge **20** kilometers closer to shore. The largest remnant (40 X 25 km) of this floe came to rest within 20 kilometers of Barter Island.

Barry, **Moritz** and Rogers (1979), using Landsat imagery, describe features at **71°N** between **149°W** and **150°W** which they interpret as a heavy ice deformation zone. These ridges were present on a Landsat image of March 25. The authors hypothesize the deformation event must have occurred in late March or early April.

Furthermore, they note that the ridge system was still in place in the same area on November 3, 1975, where it was incorporated into the fast **ice** forming with the onset of the 1975-76 winter. This ridge system was so large that it remained in place for two successive winters and it had the effect of sheltering Harrison Bay from ridge formation within its borders.

The deformation event hypothesized by Barry et al. to have resulted in this large ridge system may also be related to the series of events described in Table 6.

Additional evidence for the uniqueness of the March 1975 events may be seen in the much more accurate measurements taken of ice displacement on the -I²S color-additive viewer. Many measurements were taken for 24 hour displacements from 1973 to 1981. For the month of March, of 71 individual measurements spanning the nine year period, only 9 (all of which occurred March 18 thru 19, 1975 and reached a maximum of 6 km/day) exceeded 1 km/day.

The events of March and April 1975 may be related to a climatic abnormality revealed in the monthly mean 700 mb height contour map (Taubensee, 1975). An area of high pressure typically located north of the Chukotsk Peninsula in March was located off the Mackenzie Delta in March of 1975. Inspection of the weekly March mean 700 mb maps for the period 1974 through 1981 revealed that a high pressure area located over Bering Strait for a week or two is a fairly common event, having occurred in five of the eight years investigated. In 1975 this condition persisted for more than a month, initially forming in the beginning of March and extending through the first week of April (Stringer and Groves, 1985).

Rogers (1978) studied the relationship between meteorological factors measured at Pt. Barrow, Alaska and summertime Beaufort Sea ice conditions between Pt. Barrow and Prudhoe Bay. He concluded that light ice summers are associated with higher than normal sea level pressure centered at 80°N, 120°W, lower than normal sea level pressure over the East Siberian Sea and with more frequent winds from the directions 135-195°. A reversal in this pressure and wind direction pattern occurs during heavy-ice summers.

Dey (1980) **has** related the extent of retreat of the ice edge in the **Beaufort** to weather conditions using NOAA imagery centered on Banks Island. He concluded that the location of pressure systems, pressure gradients, and wind direction and speed **are** the principal causes of **areal** and temporal variations in the summer ice cover.

In particular, Dey demonstrated using 1000 mb contour maps from the Canadian Atmospheric Environment Service that an area of high pressure at **75°N, 140°W** (near Banks Island) generated strong easterly and southeasterly winds over the southern Beaufort Sea and caused extensive open water off the Beaufort coast **in** August 1977. These winds were accompanied **by** higher than normal temperatures.

The mean **700 mb** pressure map for March 1975 (**Taubensee, 1975**) shows a high pressure region centered **at 75°N, 140°W**. Inspection of daily surface weather maps from the Canadian Atmospheric Environment Service reveals that for most of March, a region of high pressure was located in a way to favor the strong easterly and southeasterly winds cited by **Dey** as responsible for the appearance of extensive open water in the eastern **Beaufort** in August 1977. These conditions were especially pronounced from March 14 through the end **of** the month.

The monthly average temperature recorded in Local **Climatological** Data for Barter Island for March 1975 was **-22.1°C**, 3.5°C higher than the 30-year mean. This is **also** in agreement with **Dey's** observation that the temperature is higher than normal in summers where there is a large northern retreat of the ice edge.

Thus, the meteorological **conditions** of March 1975 were quite similar to those associated with the summertime conditions which produce **light-**ice years. It is **only** unusual that these conditions should appear in the spring.

The events of 1975 demonstrate how complimentary the particular strengths of NOAA and **Landsat** imagery may **be to** one another. **It is** doubtful one could have understood the **small scale** events apparent in the high resolution **Landsat** images of **April** 4 and 5 as **well**, if one did not have the daily **low** resolution but broad geographic coverage **of** NOAA images preceding them.

The years **1981** and **1978**, which can be characterized **as** active years, were examined for exceptional events which might be correlated to the creation of ridges which could possibly be detected on Landsat imagery.

Figure 2 reveals a large westward ice displacement off the MacKenzie Delta between March 9 and 14, 1978 which was followed by an eastward displacement. This is another instance where it was possible to use Landsat imagery to identify a feature in the ice which subsequently became a major ridge system. Landsat image 21146-20265 (78/10) of March 13 reveals an open, ice-filled lead which apparently became a ridge system (Landsat image 30017-20531, 78/10) by March 22.

In addition to the extreme event described here, at least two other extreme events occurred in 1975:

- 1) A study of average and dominant ice cover for the period June through the first two weeks in October reveals that the ice never **really** "went out" in the summer of 1975 (Stringer and Groves, 1985). This is particularly conspicuous for the second two weeks in September when the coast of Alaska is **almost** always ice free.

- 2) In the spring of 1975, the **Chukchi Polynya** was frequently very large. On February 24 it extended from Bering Strait to Pt. **Barrow** and occupied an area of 36,100 square kilometers (Stringer and Groves, 1985).

CONCLUSIONS

1) The Cape Bathurst Polynya was observed to open over a range of at least 55 km to at least 237 km from mid-February to early June, a period usually associated with maximum ice cover in the Beaufort Sea. The average opening during this period was 134 km with a standard deviation of 55 km. Much of this opening is frozen over as the opening takes place. Since the polynya is approximately 500 km in extent from north to south, on the average, the opening of the polynya results in the formation of $67 \times 10^4 \text{ km}^2$ of new ice. Although opening of the polynya is related to westward movement of ice in the Beaufort Sea, a great deal of compaction takes place throughout the east-west extent of the sea so that total westward ice movement at Barrow is not equal to total opening of the polynya.

2) At least twice in the eight year period examined, Landsat imagery was available which could be interpreted to suggest ridge buildup within the pack ice is a possible consequence of large westward ice displacement.

3) Very large floes broke off the fast ice once in the eight year period examined. The removal of these large floes resulted in a significant effect on the nearshore environment by greatly altering the extent of fast ice.

4) A number of anomalous events in the spring of 1975 may be associated with the appearance of a region of high pressure which remained over MacKenzie Bay for an unusually long time.

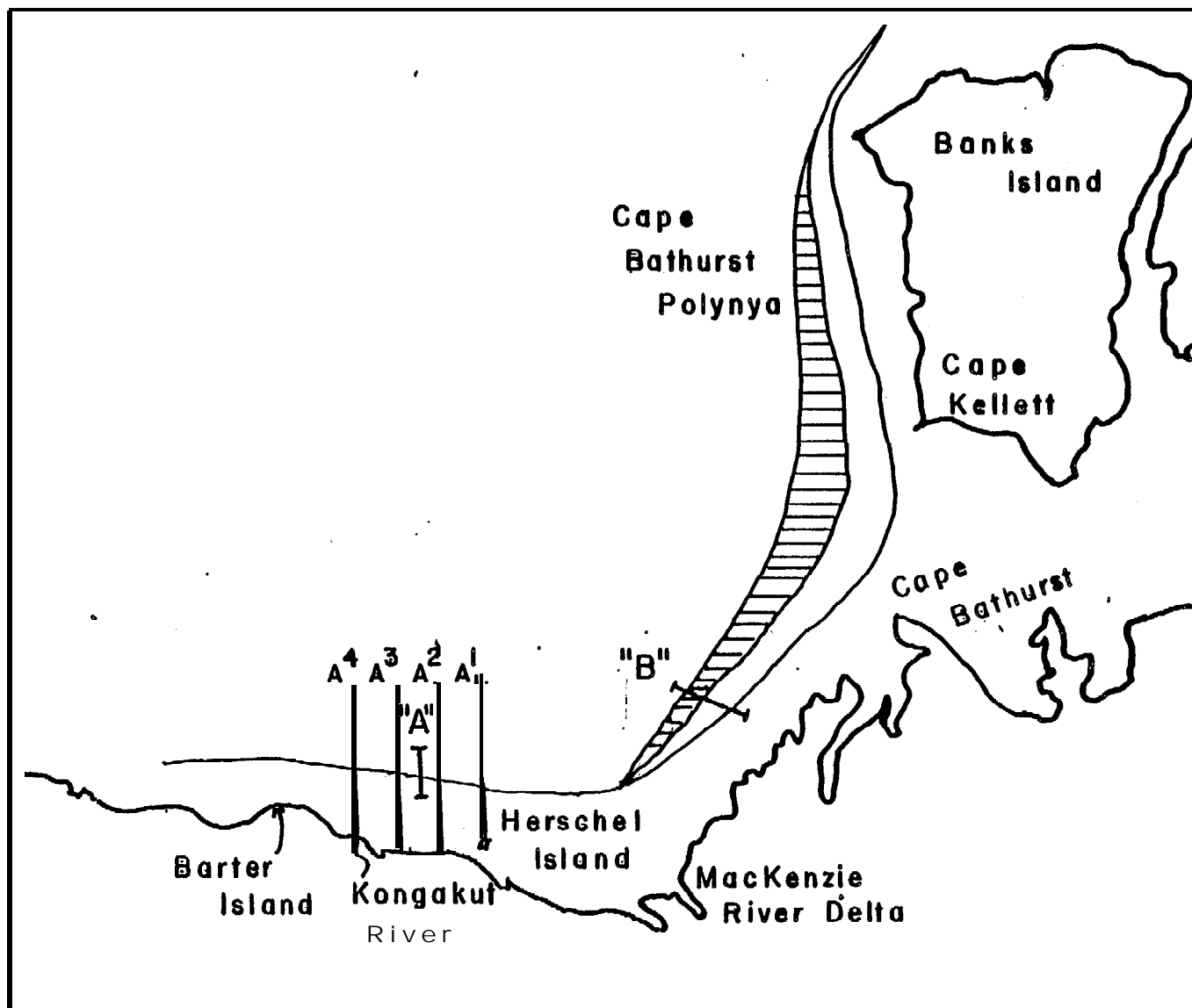


Figure 1. Location of ice displacement measurement sites on a generalized representation of the Cape Bathurst Polynya.

CUMULATIVE ICE DISPLACEMENT THE KOLYUKUT RIVER (NOAA IMAGERY)

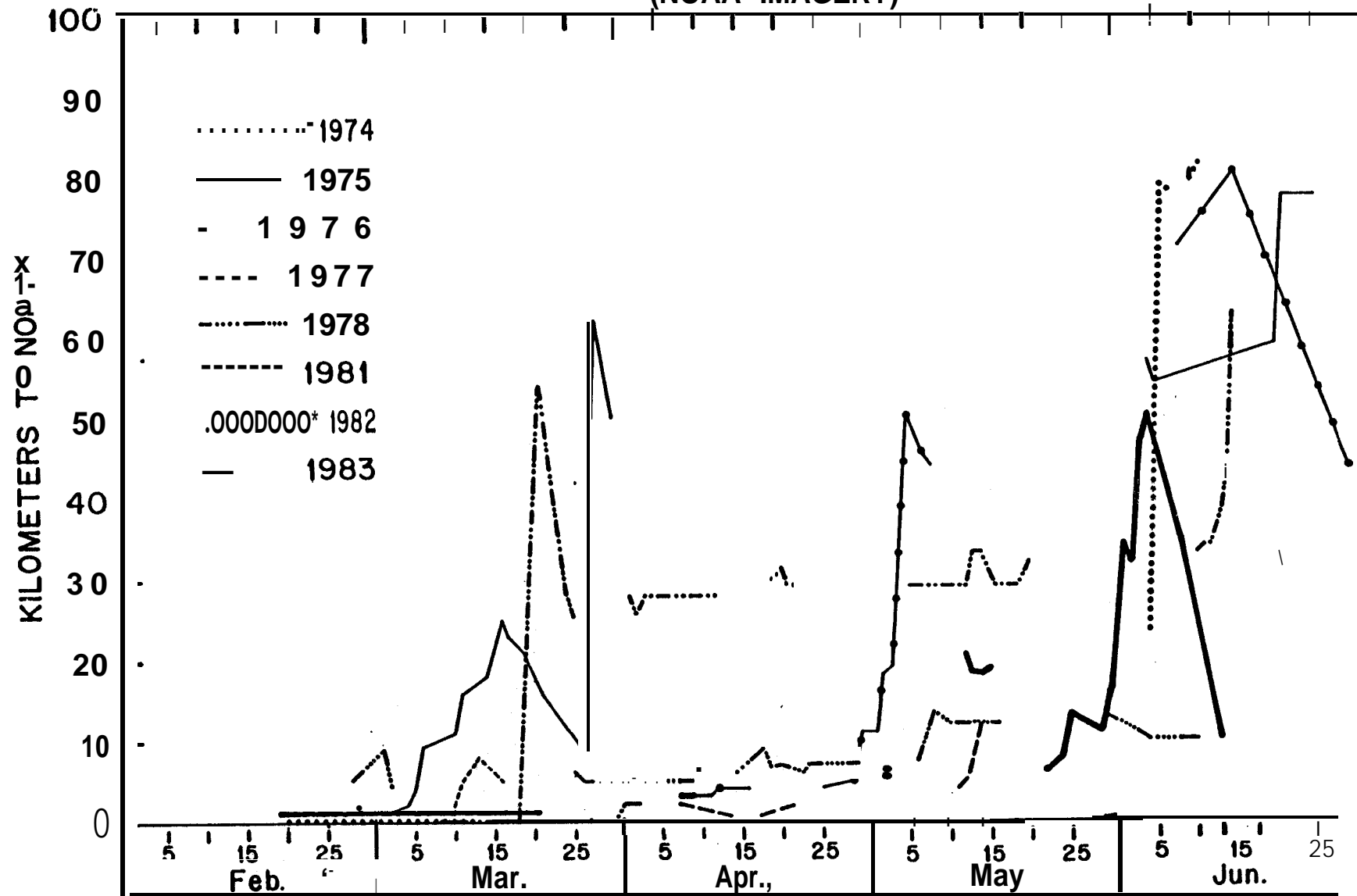


Figure 2.

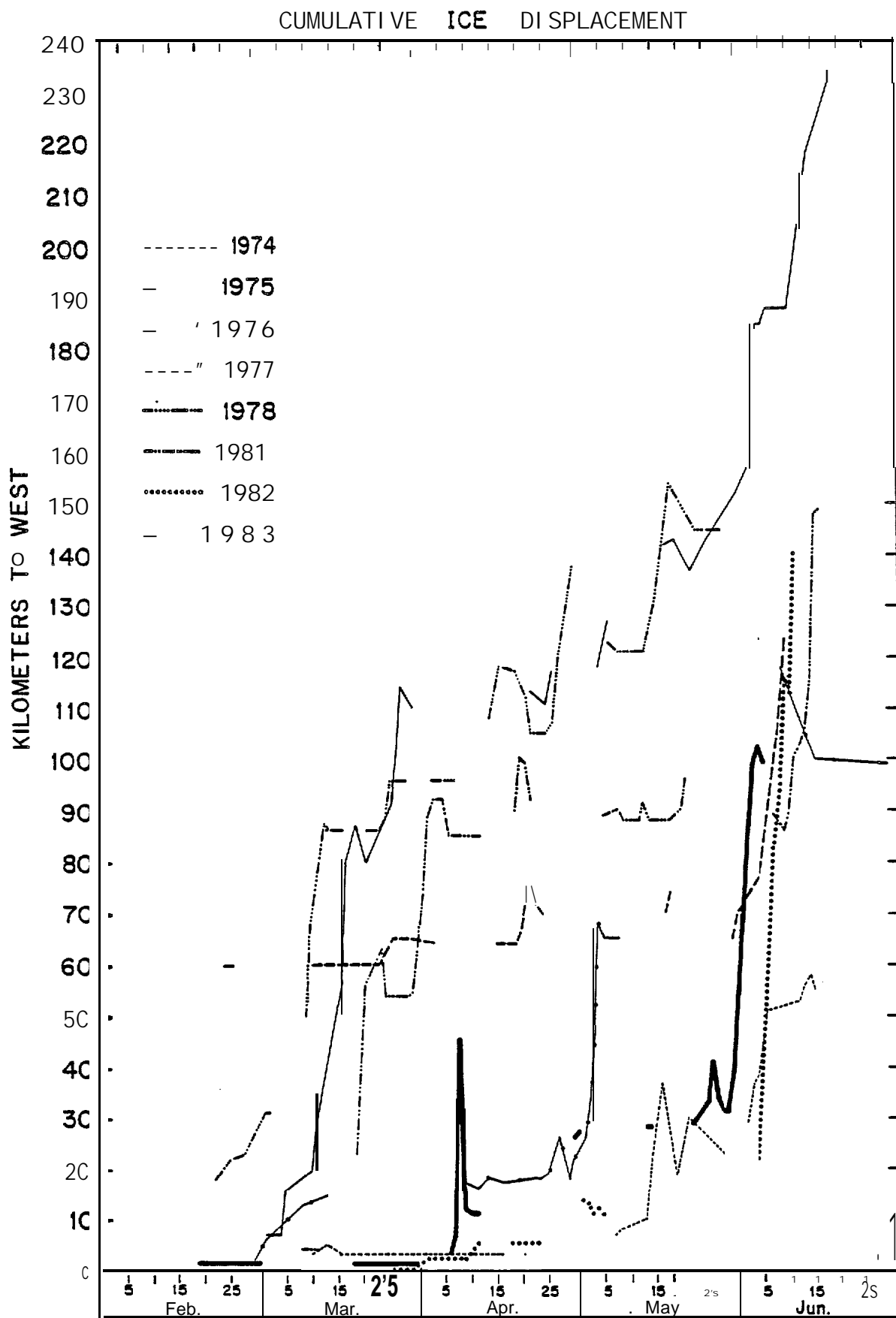


Figure 3.

Figure 4. A large floe breaks off the fast ice just above the MacKenzie Delta on March 15, 1975 (NOAA imagery).

Figure 5. The position of the floe on March 26 as it travels westward, parallel to the coastline of western Canada and Alaska. This image also reveals the banded appearance typical of a lead which is freezing as it opens above the MacKenzie Delta. An unusual feature present here is the extensive lead connecting the Bering Strait with Banks Island (NOAA imagery).



Figure 4.



Figure 5.

Figure 6. Two very large floes break off the fast ice near Herschel Island and off the Kongakut River Delta on March 28. The March 15 floe is barely visible under clouds between the two large floes. The lead connecting the Bering Strait and Banks Island associated leads have closed indicating perhaps some offshore ice movement. Note the banded appearance of a lead above the MacKenzie Delta.

Figure 7. Pieces of the floes first visible on March 28 as they appeared north of the Kongakut River Delta on April 5. One can see three large pieces of the March 28 floes and the tip of the March 14 floe. The cropping necessary to make a photograph from Landsat imagery allowed no more than this much of the March 14 floe to be shown. A ridge is visible north of the pieces.



Figure 6.



Figure 7.

Figure 8. A diagram illustrating the ice features located on Landsat imagery between Barter-Island and Herschel Island on March 15-18 and April 4 and 5, 1975.

- 1) Ice movements to the west on paths I, II, III and IV are given in Table 4.
- 2) The lines A^1 , AZ, A^3 , and A^4 correspond to the lines in Figure 1 used for measurement of the northward movement of the pack ice recorded in Table 1. These lines were also used to study the variability of northward movement of the pack ice when measured at different points along the coast (Table 3) and for comparison of the utility of NOAA and Landsat imagery for measuring distances and rates of movement (Table 6).
- 3) The ridges of April 5 may be seen in Figure 7.

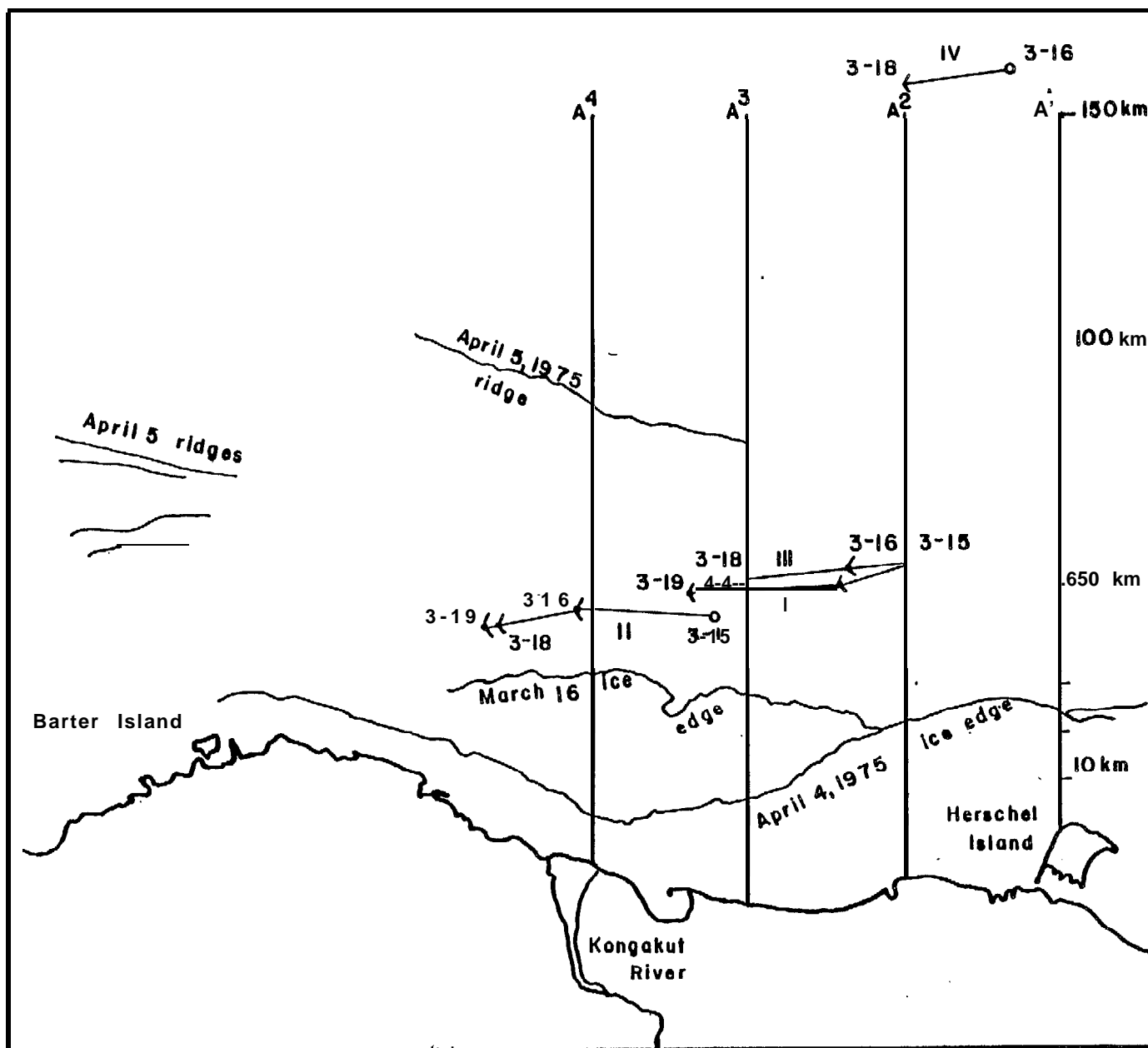


Figure 8.

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TABLE 1
NET CUMULATIVE ICE DISPLACEMENT (NOAA IMAGERY)

<u>Year</u>	Kongakut River	MacKenzie Delta
	<u>Net Cumulative Movement North</u>	<u>Net Cumulative Movement West</u>
1974	5 km	55 km
1975	78 km	237 km
1976	80 km	99 km
1977	0 km	122 km
1978	10 km	173 km
1981	67 km	149 km
1982	81 km	140 km
1983	35 km	99 km
	Average = 44.5 $\sigma = 36$	Average = 134 $\sigma = 55$

TABLE 2
PERCENTAGE OF IMAGES "SUITABLE FOR USE
IN THE MACKENZIE DELTA

<u>Period</u>	<u>Useful Images</u>	<u>Days in Period</u>	<u>Percentage</u>
3/10 - 6/15 1974	44	92	48%
3/1 - 6/20 1975	52	122	43
2/29 - 6/15 1976	28	108	26
2/24 - 6/17 1977	30	112	27
2/22 - 6/15 1978	47	112	42
3/8 - 6/16 1981	49	99	49
2/20 - 6/11 1982	35	110	32
2/16 - 6/8 1983	36	111	32

TABLE 3
MEASUREMENTS OF OPENINGS (NOAA IMAGERY)

Date 1975	Width in km at four locations north of Demarcation Pt.*				Width in km off the MacKenzie Delta**		Rate of Change, km/day					
	A ¹	A ²	A ³	A ⁴	B ^W Open water alone	B ^T Total width	A ¹	A ²	A ³	A ⁴	B ^W	B ^T
March 25	24 km	6.3 km	Clouds	Clouds	6.3 km	86 km						
March 26	33	18	7.2	2.7	3.6	90	9	12			-2.7	4
March 27	2.7	12	0.9	4.5	13	101	-30	-6	-6	2	10	11
March 28	23	39	26	2.5	11	137	20	27	25	20	-2	36
March 29	20	50	40	25	14	140	-3	11	14	0	3	3
March 30	28	40	59	54	13	170	8	10	19	29	-1	30

* Locations of A¹, A², A³, and A⁴ on Figure 1.

** Location of B on Figure 1.

TABLE 4

COMPARISON OF MEASUREMENTS FROM LANDSAT AND NOAA IMAGERY FOR THE OPENING OF
A LEAD NORTH OF DEMARCATION POINT

Imagery	Date 1975	Width of lead			Rate of lead opening		
		A ¹	A ²	A ³	A ¹	A ²	A ³
NOAA	March 15	27 km	25 km	7 km	---	---	---
	March 16	23 km	28 km	15 km	-4 km/day	+3 km/day	+8 km/day
LANDSAT	March 15	26 km	21 km	14 km	---	---	---
	March 16	21 km	24 km	19 km	-5 km/day	+3 km/day	+5 km/day

TABLE 5

ICE DISPLACEMENTS MEASURED OFF HERSCHEL ISLAND AND OFF THE MACKENZIE DELTA

Date 1975	Rate off MacKenzie Delta (NOAA) km/day W.		Rate near Herschel Island (Landsat) km/day W.				
	Lead opening*	floe movement**	I ***	II ***	III***	IV***	V
rch 14 16	---	12	---	---	---	---	---
rch 15 16	5	---	16	30	13	---	---
rch 16 18	9	---	16	8	13	11	---
rch 16 18	13	27	---	---	---	---	---
rch 17 18	4	---	---	---	---	---	---
rch 17 22	---	9	---	---	---	---	---
rch 18 19	12	---	3.5	3.2	5.5	---	6

As determined by measuring widening of a lead visible on NOAA imagery

As determined by following the March 14 floe moving in open water

* Location shown in Figure 8

A flow which is just breaking off the pack ice

A floe which is moving in open water

The pack ice within 75 km of the coast

A small floe within a lead in the pack ice greater than 75 km from the coast

Very accurate measurements of ice displacements using the 1²S color additive viewer

- Signifies that measurement was not possible due to absence of imagery

TABLE 6
MOVEMENT OF A FLOE WESTWARD FROM THE MACKENZIE DELTA

te 75	Distance Travel ed	Commentary
rch 14		A floe breaks off from the fast ice near the Mackenzie Delta; this floe is approximately 200 km ² and located at 70°N, 136°W.
rch 14 to rch 16	23 km/2 days or 12 km/day	
rch 16 to rch 17	27 km/day	
rch 17 to rch 22	18 km/5 days or 3 km/day	
rch 22 to rch 26	17 km/4 days or 4 km/day	
rch 28		Two large floes (1000 km ² and 650 km ²) Break off the fast ice somewhat westward of the first floe.
rch 26 to rch 30	56 km/4 days or 14 km/day	
rch 30 to ril 2	28 km/3 days or 9 km/day	Sometime in this period the three large floes above collided with the pack ice north of Demarcation Point.
ril 4		Water freezes. Movement prior to this data may be considered representative of the current; movement after this date is representative of the work of the current on the-pack ice.
ril 2 to ril 21	No movement	
ril 21 to y 15	25 km/24 days or 1 km/day	
ry 15 to ne 2	No motion	194 km traveled by the floe; no motion detected after June 2 because floe hard to find

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